

Recent Progress in Lorentz and CPT Violation

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This contribution to the CPT'16 meeting briefly highlights some of the recent progress in the phenomenology of Lorentz and CPT violation, with emphasis on research performed at the Indiana University Center for Spacetime Symmetries.

1. Introduction

In the three years since the CPT'13 meeting, interest in the idea of Lorentz and CPT violation has continued unabated, driven by the notion that tiny detectable violations of Lorentz symmetry could yield experimental information about Planck-scale physics. New results drawn from many subfields are appearing on the timescale of weeks, often announcing sensitivity gains of an order of magnitude or more, and making the subject among the more rapidly developing areas of physics. One simple measure of the rate of progress during these three years is the increase of over 40% in length of the *Data Tables for Lorentz and CPT Violation*,¹ which collates experimental measurements in all subfields. Here, I outline a few essentials of this active subject and briefly highlight some of the recent research performed at the Indiana University Center for Spacetime Symmetries (IUCSS).

2. Essentials

At least two philosophically different approaches can be envisaged in describing a new phenomenon. One is to develop a specific model and study its predictions. This method is well suited to situations where an experimental effect is confirmed. However, given the present lack of compelling evidence for Lorentz violation, it is appropriate to adopt a more general alternative method, developing a realistic framework encompassing all violations of Lorentz and CPT symmetry to guide a broad experimental search.

Effective field theory provides a potent tool for describing small signals emerging from an otherwise inaccessible scale.² The comprehensive effective

field theory for Lorentz violation that integrates coordinate independence, realism, and generality is called the Standard-Model Extension (SME).^{3,4} The SME can be constructed from the action of General Relativity coupled to the Standard Model by adding all Lorentz-violating and coordinate-independent terms. These can arise explicitly or spontaneously in a unified theory such as strings,⁵ and they incorporate general CPT violation.^{3,6}

Each SME term comes with a coefficient for Lorentz violation governing the size of the associated experimental signals. A coefficient can be viewed as a background that affects the properties of particles according to their flavor, velocity, spin, and couplings. The effects of the coefficients are expected to be tiny, either through direct suppression or through ‘counter-shading’ by naturally weak couplings.⁷ Experimental constraints now exist for many coefficients,¹ some at Planck-suppressed levels or beyond.

Terms in the SME Lagrange density include Lorentz-violating operators of arbitrary mass dimension d . Restricting attention to operators of renormalizable dimension $d \leq 4$ yields the so-called minimal SME.^{3,4} The explicit construction of the numerous operators for arbitrary $d > 4$ has been accomplished for several sectors, including terms associated with the propagation of gravitons, photons, Dirac fermions, and neutrinos.⁸

To preserve conventional Riemann or Riemann-Cartan geometry, the Lorentz violation must be spontaneous.⁴ This implies that massless Nambu-Goldstone modes appear, with accompanying phenomenological effects.⁹ The conjecture⁴ that explicit Lorentz violation is associated instead with Finsler geometry has gained recent support¹⁰ but remains open to date.

3. Recent IUCSS progress

At the IUCSS, much of the focus during the last three years has been on the gravity, photon, matter, and quark sectors. In the gravity sector, the nonminimal pure-gravity terms for $d \leq 6$ have recently been constructed.¹¹ They modify gravity at short distances, and in the nonrelativistic limit the effects are controlled by 14 independent coefficients. In a series of experimental advances during 2015 and 2016, the first combined sensitivities to these coefficients were reported, and individual bounds then further improved by about two orders of magnitude.¹² In a different vein, all contributions to the graviton propagator were constructed for arbitrary d ,⁸ including both Lorentz-invariant and Lorentz-violating terms. These reveal anisotropic, dispersive, and birefringent modifications to gravitational-wave propagation, which are constrained partly by observational data. An-

other source of strong bounds on SME coefficients in the pure-gravity sector comes from the highest-energy cosmic rays, which constrain gravitational Čerenkov radiation.¹³ Nonetheless, much of the coefficient space in the gravity sector remains open for future exploration.

Tests of Lorentz symmetry with light and matter have the longest history but continue to set record sensitivities. In the minimal photon sector, an improvement in sensitivity of some four orders of magnitude has been achieved in recent months using data from one of the LIGO instruments,¹⁴ showing that Planck-suppressed effects on the propagation of light can be accessed by the world's largest interferometers. In the nonminimal photon sector, astrophysical measurements have bounded individually all $d = 6$ nonbirefringent effects,¹⁵ and results constraining all $d = 5$ coefficients are within reach. The phenomenology of the nonminimal matter sector has also recently seen significant progress. Spectroscopic methods for hydrogen, antihydrogen, other hydrogenic systems, and exotic atoms provide constraints from existing data and offer access to many unmeasured coefficients, as do studies of particles confined to a Penning trap.¹⁶

In the quark sector, limits on Lorentz and CPT violation are comparatively few to date. Most have been obtained from meson interferometry, which offers a unique sensitivity to certain quark coefficients.¹⁷ The past few years have seen improved measurements on d - and s -quark coefficients using kaons and first bounds on b quarks from both B_d and B_s mixing.¹⁸ The t quark decays too rapidly for mixing and hence its Lorentz properties were unknown until recently, when studies of $t\bar{t}$ pair production and decay yielded first constraints on t -quark coefficients.¹⁹ It has now been shown that this result could be improved in experiments at the Large Hadron Collider, and the first test of CPT in the top sector could be performed using single- t production.²⁰ Different avenues to investigating the quark sector are also being explored. One is using deep inelastic scattering, from which bounds on u - and d -quark coefficients can be extracted.²¹ Another is using chiral perturbation theory, which can connect hadron coefficients to quark coefficients.²² Both these approaches offer the potential for a significant expansion of our understanding of Lorentz and CPT violation in quarks. The prospects for future discovery are bright.

Acknowledgments

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